Assessment of Heavy Metal Inhalation Risks in Urban Environments in Poland: A Case Study

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ABSTRACT

In recent years, heightened air pollution characterized by elevated levels of particulate matter and potentially toxic metals has become a prominent concern, particularly in densely populated urban areas, which may pose a threat to the health of the population. The present study aims to conduct a comprehensive health risk assessment of heavy metals exposure via inhalation, with a focus on submicron particles (PM_1), in two major cities of Poland - Warsaw and Zabrze. These cities were selected due to their distinct levels of urbanization and industrialization. Non-carcinogenic and carcinogenic risks assessment was performed for children and adults. The carcinogenic risk was evaluated for As, Cd, Cr(VI), Ni, Pb, and Co, classified as carcinogens, the non-carcinogenic risk evaluation encompassed a broader range of metals, including V, Mn, Cu, Zn, and Mg, aiming to comprehensively understand health exposure. The results highlight elevated carcinogenic risk in Zabrze, primarily linked to industrial activities and ongoing emissions. Notably, Ni, As, and Cr(VI) exceed safe limits, underscoring the need for targeted interventions. Moreover, non-carcinogenic risks reveal Zabrze's heightened respiratory health risks, compared to Warsaw. Despite Warsaw's lower non-carcinogenic risk values, both cities recorded Ni and Mg concentrations exceeding safe limits. This indicates that Zabrze faces higher health risks from heavy metal exposure due to ongoing pollution sources. In contrast, Warsaw, the capital city and a major urban centre, demonstrates better air quality but still requires continuous monitoring and pollution control measures.

Keywords: air pollution, submicron particles, health risk, carcinogenic risks, non-carcinogenic risk

INTRODUCTION

Air pollution, primarily driven by the emissions of particulate matter (PM), polycyclic aromatic hydrocarbons and heavy metal(loid)s, is recognised as a significant environmental health concern worldwide. Elevated levels of air pollution have been associated with a wide range of adverse health effects, impacting children and adults. As urbanisation continues to accelerate, leading to the proliferation of large metropolitan areas (Eurostat, 2023). As more people move to cities seeking better opportunities, the concentration of pollutants in the air intensifies, exacerbating the already alarming air quality situation (OECD, 2023). The escalating emission of pollutants from vehicular traffic, industrial facilities, and other human activities further compounds the

challenges posed by air pollution in urban environments (Adami et al., 2022; WHO, 2021). Consequently, the health implications of prolonged exposure to air pollution have become a pressing public health concern for residents, particularly those residing in major cities (Adami et al., 2022).

PM, often categorised based on their aerodynamic diameter, includes PM_{10}, $PM_{2.5}$, and the finer PM_1 particles (Talbi et al., 2018; US EPA, 2023a). These particles can easily penetrate deep into the respiratory system, causing respiratory and cardiovascular issues, exacerbating chronic conditions such as asthma, and increasing the risk of premature mortality (Adami et al., 2022). Moreover, PM_1, being the smallest and most inhalable fraction, has been recognised as a potentially more harmful component of PM due to its ability to bypass the body's natural defence mechanisms and directly enter the lungs (Li T. et al., 2022; Mainka & Zajusz-Zubek, 2019).

Alongside PM, potentially toxic metals (PTMs), such as lead, cadmium, nickel, chromium, and arsenic, have emerged as significant contributors to air pollution in urban areas (US EPA, 2023a). PTMs, often referred to as "heavy metals," are electropositive elements and metalloids present in various ecosystems, characterized by high density, that can be harmful even at trace levels, posing health risks to humans and other organisms (Appenroth, 2015; Raychaudhuri et al., 2021; Santos et al., 2018). These toxic elements are released into the atmosphere through a variety of anthropogenic sources, including industrial processes, fossil fuel combustion, and waste incineration (WHO, 2021). Once inhaled, these metals can accumulate in the body over time, leading to chronic health issues and impairing various physiological functions (Li T. et al., 2022). The carcinogenic properties of certain PTMs, notably As, Cd, Cr(VI) and Ni, raise additional concerns regarding their potential to induce cancer in exposed individuals (Balali-Mood et al., 2021; Kim et al., 2015; Samet et al., 2020).

Given the severe health consequences of air pollution, efforts to comprehensively assess the risks and identify effective mitigation strategies are of paramount importance. Monitoring and research endeavours to quantify PM_1 and PTM concentrations, evaluate exposure patterns, and understand their health impacts have become crucial in formulating evidence-based policies and regulatory measures (US EPA, 2023a; WHO, 2021). By fostering collaborations between researchers, policymakers, and urban planners, it is possible to devise innovative solutions to curb pollution levels and protect the well-being of urban populations (WHO, 2021).

In this context, the current study focuses on two distinct Polish cities, Warsaw and Zabrze, representing diverse urban settings with varying degrees of industrialization and urbanization. Both Warsaw and Zabrze have their unique characteristics and air quality challenges. Warsaw, the more densely populated capital city, faces a mix of emissions from various sources typical of large urban centres (Kais et al., 2021; Nazar et al., 2022). Zabrze, on the other hand, has experienced a transformation from a heavily industrial city to a more diverse economy, but its past industrial activities continue to influence its air quality (Hoffman et al., 2022; Michalski & Pecyna-Utylska, 2022). Studying these two cities will provide valuable insights into air pollution patterns and the potential impact on public health in both urban and industrial settings.

The present study aims to conduct a comprehensive health risk assessment of PTMs (As, Cd, Cr, Ni, Pb, Co, V, Mn, Cu, Zn, and Mg) via inhalation, with a focus on PM_1, in two major cities of Poland – Warsaw and Zabrze. These cities were selected due to their distinct geographical locations and varying levels of industrialization, making them ideal candidates for comparative analysis. The comparison between Warsaw and Zabrze will provide valuable insights into regional disparities in air quality and health risks, contributing to the broader understanding of the impact of air pollution on urban environments.

MATERIALS AND METHODS

Study area

The study was conducted in two cities: Warsaw (50º18'31.015"N, 18º47'10.95"E) and Zabrze (50º18'31.015"N, 18º47'10.95"E). These locations were selected based on meeting the criteria for urban background location specified in Directive 2008/50/EC. The topographic and meteorological conditions, as well as the structure and magnitude of emissions from particulate and gaseous pollutants, including local emissions at the sampling point, were typical for the entire agglomeration.

Zabrze is located in the southern region of Poland, specifically within the Upper Silesian Industrial District. The area's population is 174349, with a population density of 2144 people/km^2 (Góralczyk et al., 2018). Due to its historical significance as a major coal mining and industrial centre, Zabrze has faced significant air pollution challenges in the past (Michalski & Pecyna-Utylska, 2022). The region has a long industrial history, which has contributed to high levels of PM and gaseous pollutants in the air. Although industrial activity has reduced over the years, the legacy of past emissions continues to influence air quality in the region (Hoffman et al., 2022).

Warsaw is situated in the central part of Poland; its geographical location makes it a significant transportation and communication hub in the country. The area has a population of 1861975, with a population density of 3602 people/km^2 (Bieńkowska et al., 2023). Warsaw, the capital city and a major urban centre, faces several air pollution challenges. The city's primary causes of air pollution are emissions from road traffic, industrial activities, residential heating, and construction (Kais et al., 2021; Majewski et al., 2018). In particular, during the winter, the city faces increased levels of air pollution due to higher energy consumption for heating purposes (Nazar et al., 2022). Despite being subject to localized emissions, Warsaw qualifies as an urban background location (European Parliament, 2008). This means that while it experiences pollution from local sources, it also reflects the regional air quality and overall air pollution levels in the agglomeration.

PM$_1$ sampling and preparation

In Zabrze, a total of 104 daily samples of PM$_1$ were collected, with 50 samples taken during the summer period from June 24 to August 24, 2014, and 54 samples taken during the winter period from January 8 to March 9, 2015. For Warsaw, a total of 107 daily samples of PM$_1$ were collected, with 51 samples taken during the summer period from June 24 to August 22, 2014, and 55 samples taken during the winter period from January 8 to March 8, 2015. The collection of PM$_1$ samples, their preparation and the measurements of As, Cd, Cr, Ni, Pb, Co, V, Mn, Cu, Zn, and Mg concentrations were carried out following the procedure described in Rachwał et al. (2020). Briefly, PM$_1$ sampling was carried out using a sampling head

(with PM inlet) equipped with a PM$_1$ jet impactor, at a flow rate of 2.3 m^3/h. Quartz fiber filters were employed as the primary means of capturing PM$_1$ particles (Ø47 mm). The filters were conditioned in a room with a relative air humidity of 45±5% and an air temperature of 20±2°C for 48 hours prior to the weighing process. The PM samples were digested in a mixture of nitric acid and hydrogen peroxide solution in a microwave oven to determine the total content of As, Cd, Cr, Ni, Pb, Co, V, Mn, Cu, Zn, and Mg. The concentration levels were then analyzed using High-Resolution Inductive Coupled Plasma-Mass Spectrometry (HR-ICP-MS).

The collected samples, inclusive of blank samples, underwent rigorous conditioning, weighing, storage, and transportation processes that strictly adhered to the QA/QC (Quality Assurance/Quality Control) protocols of the reference method for gravimetric measurements (US EPA, 2008). Table 1 illustrates the Limit of Detection (LOD) for the studied elements, which exhibited recovery rates ranging from 88% to 107%.

Human health exposure assessment

In this study, the human health exposure assessment evaluated the non-carcinogenic and carcinogenic risks associated with inhalation exposure for both children and adult residents.

Among studied PTMs, As, Cd, Cr (VI), and Ni have been classified as Group 1 carcinogens by the International Agency for Research on Cancer (Samet et al., 2020). Additionally, Pb and Co have been categorized as Group 2A carcinogens, indicating that they are considered "probably carcinogenic to humans" by the IARC categorisation. Hence, for these specific metals, the carcinogenic risk was assessed, taking into account the inhalation unit risk (IUR) values provided by the Environmental Protection Agency (US EPA, 2023b).

The non-carcinogenic risk via inhalation was estimated for the same elements as the carcinogenic risk (i.g. As, Cd, Cr(VI), Ni, Pb, and Co) along with additional V, Mn, Cu, Zn, and Mg, as the assessment aimed to comprehensively understand the overall health exposure assessment. These PTMs were considered due to their potential health effects, particularly concerning respiratory and other non-cancer-related health impacts, especially in industrial regions (e.g., the studied city of Zabrze), where elevated levels of these metals in the air have been observed.

In the study, the total content of Cr in PM$_1$ was determined. However, Cr(VI) is recognized as a carcinogen with potentially higher health risks compared to Cr(III). Nevertheless, according to studies Widzewicz et al. (2016), it is assumed that the content of Cr(VI) in PM$_1$ constitutes 1/4 of the total chromium content in the form of Cr(III) and Cr(VI). Considering the above, the Cr(VI) value has been estimated to calculate the non-carcinogenic and carcinogenic risks.

The exposure concentration

The exposure concentration (EC$_i$) of harmful PTMs due to inhalation was calculated using the following equation:

$$EC_i = \frac{C_i \times ET \times EF \times ED}{AT_n} \qquad (1)$$

The variable C_i refers to the level of metal concentration found in PM$_1$ (µg/m^3). ET stands for exposure time, equivalent to 24 hours per day. EF refers to the frequency of exposure for metals in the study, precisely 180 days per year. ED is the exposure duration, which is 6 years for children and 24 years for adults. AT$_n$ is the average time, for non-carcinogens, is calculated as ED multiplied by 365 days and 24 hours per day; for carcinogens, the average time is 70 years multiplied by 365 days per year and 24 hours per day.

The potential risk of carcinogens

The equation used to calculate the risk of developing cancer due to inhalation of PTMs was calculated as follows:

$$CR_i = IUR_i \times EC_i \qquad (2)$$

The value of EC$_i$ represents the exposure concentration, while IUR is the inhalation unit risk measured in µg/m^3 (given in Table 1). The obtained CR$_i$ values can be evaluated against a scale, where a CR$_i$ of 1×10^{-6} is regarded as posing a negligible risk. CR$_i$ values within the range of 1×10^{-6} to 1×10^{-4} are deemed tolerable for regulatory purposes. Conversely, a CR$_i$ exceeding 1×10^{-4} is expected to have a harmful effect on human health, and corrective actions may be required.

The potential risk of non-carcinogens

To estimate the non-cancer risk of PTMs through inhalation, a hazard quotient (HQ) was calculated using the following equation:

$$HQ_i = \frac{EC_i}{RfC \times 1000} \qquad (3)$$

The EC_i value indicates the exposure concentration, whereas RfC stands for reference concentration via inhalation exposure (mg/m^3) of the specific metal component (listed in Table 1). In order to evaluate the potential non-carcinogenic impacts of a substance found in the air, the hazard index (HI) is assessed quantitatively. This index is determined by summing up the hazard quotients (HQ) of each metal being evaluated, providing a comprehensive understanding of the potential health risks posed by PTMs. When the HQ value exceeds the safe limit, e.g., 1, it indicates a likelihood of exposure to a specific metal component associated with non-carcinogens risks. Conversely, if the HQ value is less than 1, it is improbable

Table 1. Inhalation toxicity values for the targeted PTMs concentrations (C$_i$) (mean ±SD), including inhalation reference concentrations (RfC) and inhalation unit risk (IUR)

Heavy metal	C$_i$		LOD	IUR*	RfC**
	Warsaw	Zabrze			
	µg/m^3	µg/m^3	µg/m^3	µg/m^3	mg/m^3
V	5.93±0.49	4.19±0.48	0.04	-	1.00E-04
Mn	2.17±0.28	5.66±0.39	0.33	-	5.00E-05
Co	0.32±0.08	0.23±0.11	0.08	0.009	6.00E-06
Ni	59.73±1.18	43.27±3.1	0.08	0.00024	1.40E-05
Cu	2.99±0.39	5.20±0.29	0.55	-	2.00E-05
Zn	17.70±2.64	42.61±4.1	1.10	-	9.00E-04
As	2.27±0.11	2.88±0.61	0.22	0.0043	1.50E-05
Cd	0.27±0.05	0.62±0.04	0.10	0.0018	1.00E-05
Pb	7.14±0.46	19.04±1.4	1.75	0.00008	5.00E-04
Cr(VI)	4.96±0.58	3.19±0.14	0.83	0.084	1.00E-04
Mg	127.81±15.34	142.45±14.83	7.61	-	1.40E-05

Note: * US EPA (US EPA, 2023b); ** ATSDR (ATSDR, 2023), OEHHA (California Environmental Protection Agency, 2009).

that exposure to the metal component will result in any adverse health effects. Additionally, if the HI value exceeds 1, there could be potential non-cancer risks, and exposure to a mixture of metals may become a concern for public health.

RESULTS AND DISCUSSION
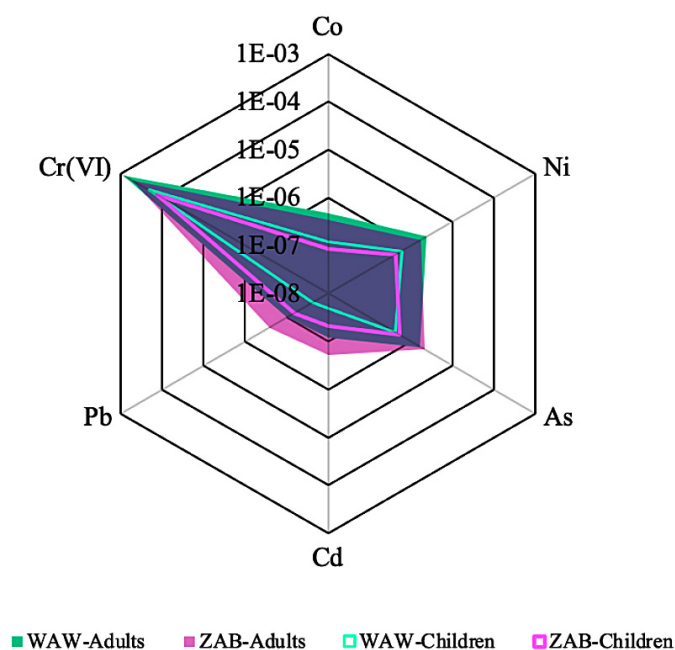
Carcinogenic risks

The obtained results of the carcinogenic risks for PTMs inhalation exposure in Warsaw and Zabrze, as well as the comparison between children and adults, are presented in Figure 1.

According to the results obtained, significant differences in the risk of cancer development through metal inhalation exposure were observed between adults and children in both cities. In both cities, the CR values for PTMs varied considerably, highlighting notable differences in risk levels. Zabrze, an industrial hub with a history of coal mining and heavy industrial activities, exhibited consistently higher CR values than Warsaw. This disparity can be attributed to the legacy of past emissions and ongoing industrial activities in Zabrze, leading to elevated levels of heavy metal pollutants in the air (Caganic et al., 2015; Klejnowski et al., 2009). The higher CR values in Zabrze suggest an increased risk of cancer development due to long-term exposure to these hazardous substances, particularly As, Cd, and Pb, compared to Warsaw.

Interesting patterns emerged when analyzing the differences in CR values between children and adults. In both cities, the CR values were generally higher for adults than children, indicating that adults may face a slightly higher risk of emerging cancer from heavy metal exposure. In the case of adults in Zabrze, a higher risk of cancer associated with the inhalation of metals such as As, Cd, and Pb were observed. For children in both cities, a higher risk of cancer associated with the inhalation of As, Cd, Pb, and Cr(VI) was observed. In Warsaw, the presence of Ni in higher concentrations among children appears to contribute to the increased risk. However, it is essential to consider that children are essentially more vulnerable to the adverse effects of environmental pollutants, and even relatively lower CR values in children can pose significant health risks (Manisalidis et al., 2020; Simeonova et al., 2021). The findings are consistent with the data observed in other urban areas, as indicated in Table 2.

Furthermore, for certain metals like Ni, As, and Cr(VI), the obtained carcinogenic risk (CR) values for adults in both cities exceeded the minimum values (i.e. 1×10^{-6}) defined by Environmental Protection Agency (US EPA, 2023b). This indicates a significant potential health risk for residents exposed to these metals, especially for children in Zabrze, CR values for As and Cr(VI)

Fig. 1. Carcinogenic risks for PTMs inhalation exposure in Warsaw (WAW) and Zabrze (ZAB) for children and adults

Table 2. Comparison of the carcinogenic risks of PTMs exposure via inhalation available in the literature for similar sampling sites

Country	City		Heavy Metals	Estimated risk value	Reference
carcinogenic risk					
Poland	Katowice	summer	As, Cr	6.02E-04	(Widziewicz et al., 2016)
		winter		5.00E-04	
Poland	Katowice	children's: site K1	As, Cd, Co, Cr(VI), Ni, Pb (mobile fractions)	7.79E-07	(Zajusz-Zubek et al., 2017)
		site K2		9.03E-07	
		site K3		1.05E-06	
		site K4		1.58E-06	
		adults: site K1		3.12E-06	
		site K2		3.61E-06	
		site K3		4.20E-06	
		site K4		6.32E-06	
Italy	Viggiano	children's	Cd, Cr(VI), Ni, Pb	3.45E-05	(Caggiano et al., 2019)
		adults		1.38E-04	
Poland	Gliwice	children's	As, Cd, Cr(VI), Mn, Ni, Sb, Se	6.05E-02	(Mainka, 2021)
		adults		4.64E-01	
China	Nanjing	children's	As, Cd, Co, Cr(VI), Ni, Pb	3.61E-06	(Li et al., 2020)
		adults		1.45E-05	
Turkey	Pendik	children's and adult	Ni, Pb, Cr(VI)	6.67E-05	(Onat et al., 2020)

exceeded the defined minimal limits, which is a severe concern for the health of the youngest inhabitants in the area. This concern is grounded in the potential health impacts of As, and Cr(VI), which has been associated with detrimental effects on cellular and genetic levels (Balali-Mood et al., 2021). As exposure elevates the cancer risk by attaching to DNA-binding proteins and impeding the DNA-repair mechanism (Mitra et al., 2022). Cr(VI) exposure leads to molecular damage within cells, primarily attributed to intracellular reduction processes (Al et al., 2019). This results in various forms of genetic mutations, including point mutations in DNA and chromosomal damage genetic mutations, combined with disrupted cellular functions, can lead to the development of cancerous tumor (Engwa et al., 2019). Significant potential health risks associated with As and Cr exposure have been observed in other cities with a comparable level of industrialization. Widzewicz et al. (2016) noted a heightened carcinogenic risk in Katowice during the summer season as opposed to the winter. The results obtained are comparable to other cities worldwide. For instance, a highly industrialized city in Italy had carcinogenic risks exceeding safe limits for both adults and children (Table 2). Analogously, according to the findings of Onat et al. (2020), a risk analysis conducted on the city of Pendik in Turkey has revealed significant health risks for all members of its community, irrespective of their age group.

The variations in CR values between cities and age groups underscore the need for targeted intervention strategies to address heavy metal pollution in urban environments. Implementing effective pollution control measures, especially in industrial regions like Zabrze, is crucial to reduce the health risks associated with PTMs exposure. Moreover, safeguarding the health of vulnerable populations, such as children, should be a priority in urban planning and policy-making to create healthier living environments.

Non-carcinogenic risks

The obtained results of the non-carcinogenic risks for heavy metal inhalation exposure in Warsaw and Zabrze are presented in Figure 2.

The results of the non-carcinogenic risks for heavy metal inhalation exposure in Warsaw and Zabrze reveal significant differences between the two cities, reflecting their distinct urban settings and pollution profiles.

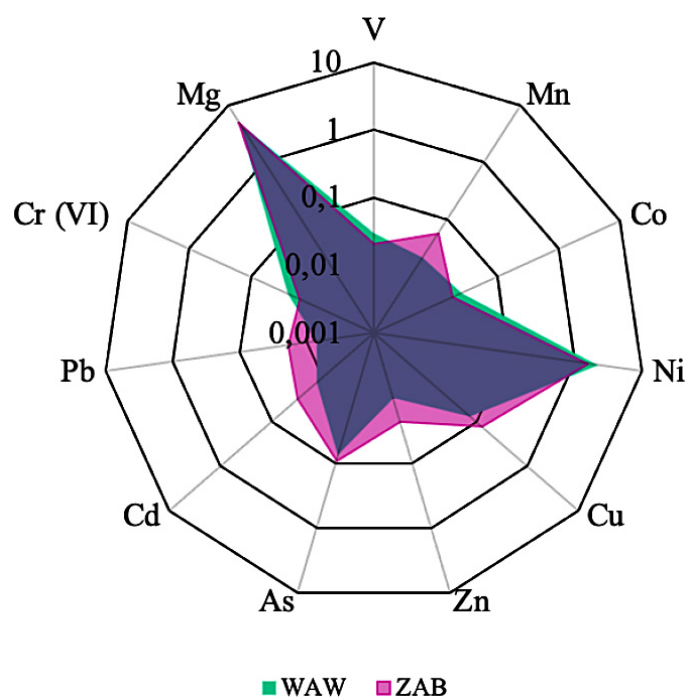It has been observed that the concentrations of Mn, Cu, Zn, As, Pb, and Mg in Zabrze are

Fig. 2. Non-carcinogenic risks for PTMs inhalation exposure in Warsaw (WAW) and Zabrze (ZAB), based on the hazard quotient

consistently higher when compared to those in Warsaw. This indicates a higher health risk associated with heavy metal exposure in Zabrze, especially for respiratory and other non-cancer-related health impacts. The history of industrial activities and coal mining in Zabrze has contributed to elevated levels of heavy metal pollutants in the air, resulting in potentially adverse health effects for the residents (Kadłubek et al., 2017; Krawczyk, 2020). On the other hand, Warsaw exhibits comparatively lower HQ values for most PTMs, suggesting a relatively lower health risk. However, it is essential to note that even though the HQ values are lower than those in Zabrze, they still indicate a potential health risk and require attention and mitigation efforts (Samet et al., 2020; WHO, 2021).

In both cases, HQ exceeded the safe limit for potential non-cancer risk exposure for Ni, and Mg. Among the evaluated metals, Ni stands out as a notable concern, exceeding the safe limit by over 2-fold in Warsaw and 1.5-fold in Zabrze. Elevated levels of Ni exposure may lead to adverse health effects, such as respiratory irritation and lung damage (Buxton et al., 2019; Genchi et al., 2020; Jaishankar et al., 2014). It is important to highlight the high levels of Mg present in both Zabrze and Warsaw. These levels exceed the safe limit by over five times in Zabrze and four times in Warsaw, indicating a significant health risk. While Mg is an essential element for the body, excessive exposure

may result in respiratory issues and impairment of lung function (Engwa et al., 2019; Manisalidis et al., 2020; Tiotiu et al., 2020).

The HI values obtained for Warsaw and Zabrze reveal potential non-cancer-related risks associated with PTM exposure. The HI values of 6.8 for Warsaw and 7.0 for Zabrze, both exceeding the threshold of 1, indicate that the combined exposure to multiple metals may pose a public health concern, particularly respiratory and other non-cancer-related health effects. This reflects the need for comprehensive measures to address and mitigate the risks posed by exposure to mixtures of PTM in urban environments such as Warsaw and industrial regions such as Zabrze. In other Polish cities e.g. Gliwice, and Katowice, with a high level of industrialization (like Zabrze), non-cancer-related risks associated with PTMs exposure have been observed (Table 3). The results are consistent with international data, as China and Italy have also reported comparable patterns in urban areas like Nanjing (Li H. et al., 2020) and Viggiano (Caggiano et al., 2019). Within these cities, non-carcinogenic risks have surpassed the established threshold value. This underscores the urgency for comprehensive strategies to mitigate the health risks associated with exposure to mixed PTMs pollutants in urban environments, as demonstrated not only in Zabrze and Warsaw but also in other urban areas worldwide.

Table 3. The non-carcinogenic risks associated with PTMs inhalation exposure in relation to data from similar sites in the literature

Country	City		Heavy Metals	Estimated risk value	Reference
Poland	Katowice	site K1	As, Cd, Co, Cr(VI), Hg, Mn, Ni, Sb, Se	2.27E-01	(Zajusz-Zubek et al., 2017)
		site K2		2.60E-01	
		site K3		3.10E-01	
		site K4		4.26E-01	
Italy	Viggiano		Cd, Cr(VI), Cu, Mn, Ni, Pb, Zn	2.87E+00	(Caggiano et al., 2019)
Poland	Gliwice		As, Cd, Cr(VI), Mn, Ni, Sb, Se	6.05E-02	(Mainka, 2021)
China	Nanjing		As, Cd, Co, Cr(VI), Mn, Ni, Tl, V	4.19E−01	(Li et al., 2020)
Turkey	Pendik		Ni, Mn, Cr(VI)	1.43+E00	(Onat et al., 2020)

It's important to remember that in polluted air, exposure to not only PTE occurs but also to other harmful substances, including carcinogenic polycyclic aromatic hydrocarbons (Badyda et al., 2018; Ciarkowska et al., 2019; Sun et al., 2021). These components have the ability to penetrate deeply into the respiratory system, collectively creating a potential risk of DNA damage and significantly increasing the likelihood of various types of cancer (de Oliveira Alves et al., 2020; Sun et al., 2021). Effective risk reduction requires a comprehensive understanding of how these substances interact within the respiratory system. This is crucial, not only for a better grasp of the mechanisms involved but also for identifying potential intervention points to minimize prolonged exposure to outdoor pollutants coupled with the influence of indoor pollution. Therefore, future research should focus on how heavy metals and polycyclic aromatic hydrocarbons interact within the respiratory system, in order to better safeguard human health.

CONCLUSIONS

This research aims to shed light on the health risks posed by PM_1 and PTMs in urban settings, emphasizing the need for comprehensive air quality management and public health interventions to ensure a healthier and sustainable urban living environment.

Higher cancer risks were observed in Zabrze compared to Warsaw, primarily due to industrial activities and legacy emissions, especially for As, Cd, and Pb. According to the results, adults generally face slightly higher cancer risks from heavy metal exposure compared to children in both cities. Certain metals, such as Ni, As, and Cr(VI), pose significant health risks, with CR values exceeding limits, emphasizing the need for targeted interventions. Zabrze exhibits higher non-carcinogenic risks, particularly for respiratory health consequences, compared to Warsaw. Although Warsaw has lower HQ values, it still indicates potential health risks from PTMs exposure. In both, Warsaw and Zabrze, the levels of Ni and Mg have surpassed the safe limit for non-cancer risk exposure. Ni exceeds safe limits in Warsaw and Zabrze by more than 2-fold and 1.5-fold, while Mg is over 5-fold and 4-fold, respectively. Both cities need targeted interventions to address these challenges; it is crucial to empower the residents of both cities to take proactive measures in their daily lives. Initiatives such as promoting eco-friendly transportation, practising indoor air quality management, and enhancing public awareness can significantly contribute to reducing PM exposure. These efforts, coupled with strategic urban planning, hold the potential to enhance overall air quality and public health, fostering healthier urban environments.

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